EM Symposium

IN HONOR OF RAJ MITTRA

Saturday, September 27, 2014

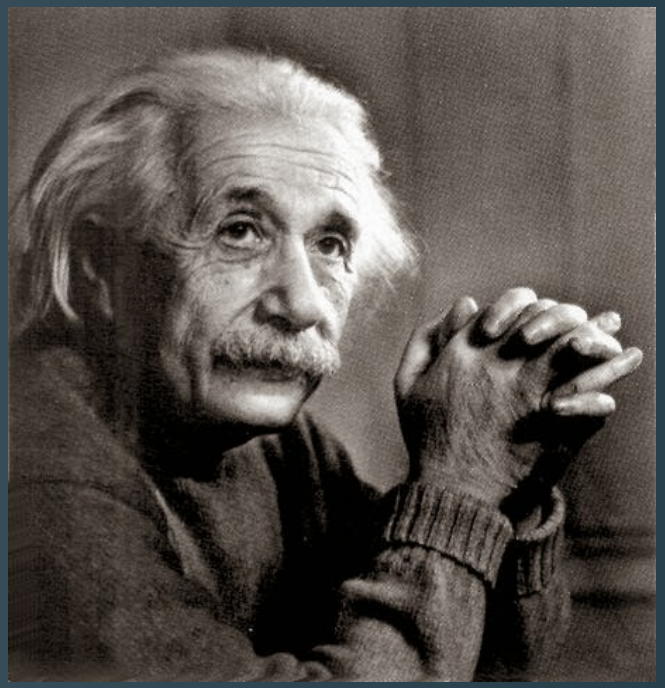
Daylong symposium and dinner

Computational Electromagnetics: Simplicity is Power

Andreas C. Cangellaris

ENGINEERING AT ILLINOIS

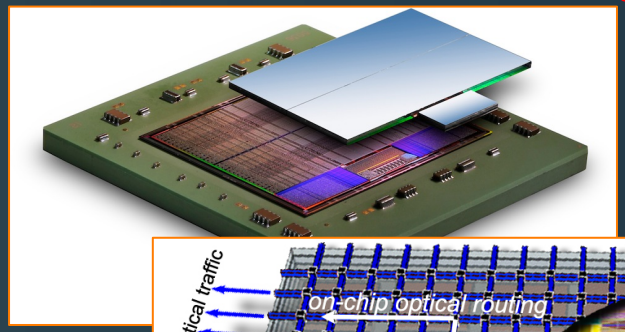
"Everything should be made as simple as possible

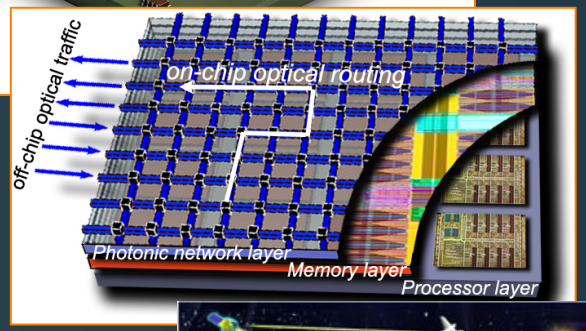


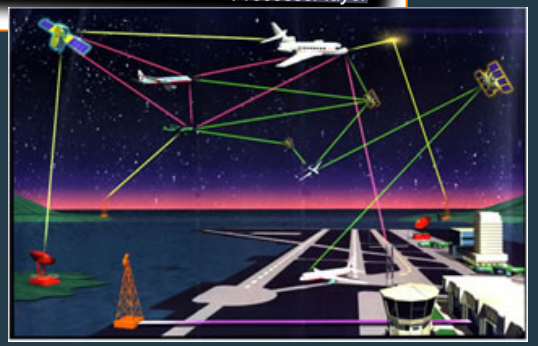
…but not simpler."

Closed-form approximations of layered media Green functions(*)

- In terms of:
  - **spherical waves** that capture the singular field behavior at the source
  - and **cylindrical waves** to represent accurately the far-field behavior
- Avoiding:
  - the separate consideration of the "far" and "close" field regions by utilizing a **single expression** for the Green's function;
  - numerical integration



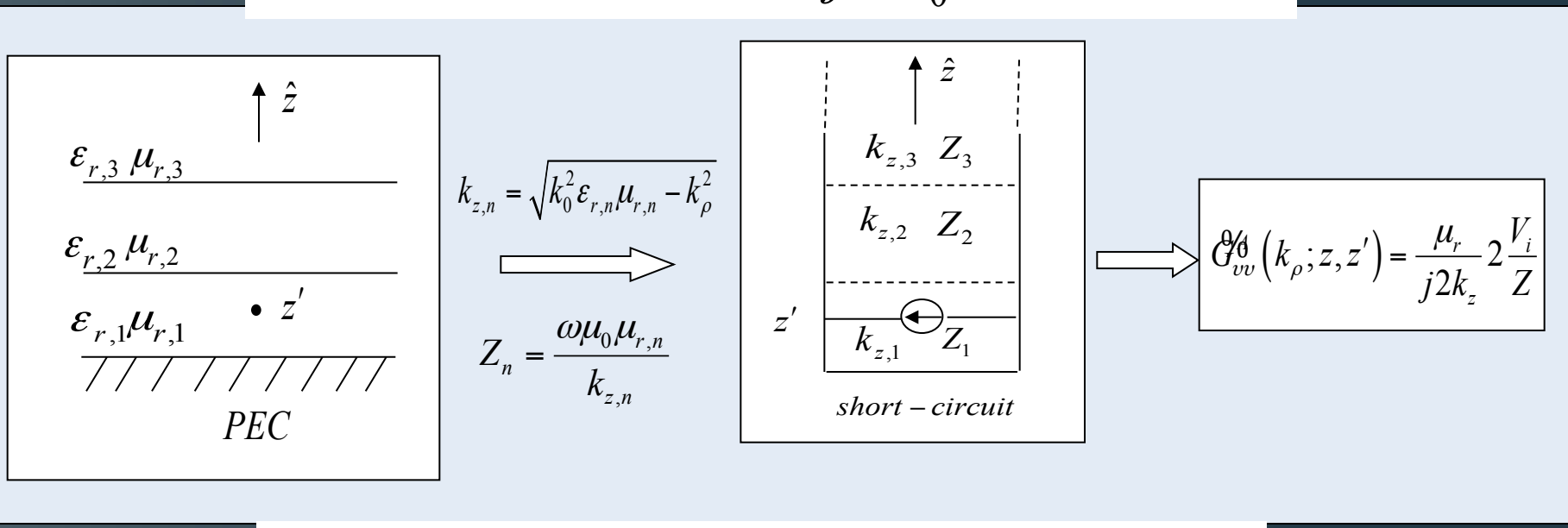




(*) V. Kourkoulos and A. Cangellaris, in *IEEE Trans. Antennas & Propagat.*, vol. 54, no. 5, pp. 1568 – 1576, 2006.

Mixed Potential Integral Formulation

$$\mathbf{E} = -j\omega\mu_0 \left\langle \bar{\mathbf{G}}^A ; \mathbf{J} \right\rangle + \frac{1}{j\omega\varepsilon_0} \nabla \left\langle K^{\Phi}, \nabla' \mathbf{J} \right\rangle$$



$$G^A_{xx}(\rho; z, z') = \frac{1}{2\pi}\int_0^\infty \tilde{G}^{\Phi}_{vv}\left(k_\rho; z, z'\right) J_0\left(k_\rho \rho\right) k_\rho dk_\rho$$

Rational function fitting of the dynamic part of the spectrum

Use of a rational function fitting algorithm (VECTFIT) to approximate the spectrum in such a way that the transition to the space domain is done in closed-form

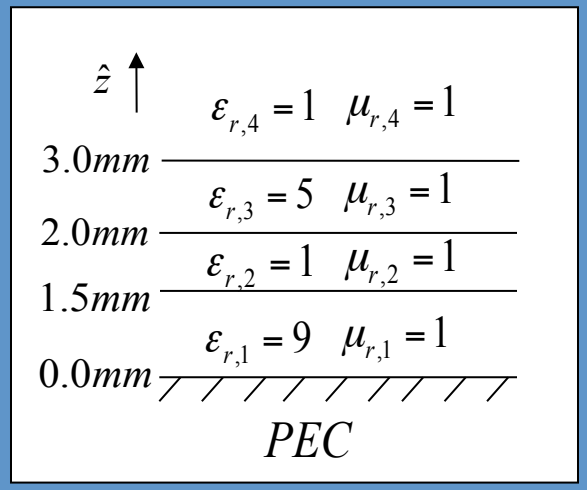
$$G_{vv,dyn}\left(k_\rho; z, z'\right) = \sum_{n=1}^{N} \frac{b_n}{k_\rho^2 - \beta_n^2}$$

$$G_{xx,dyn}^{A}\left(\rho; z, z'\right) = -\frac{j}{4} \sum_{n=1}^{N} b_n H_0^{(2)}\left(\beta_n \rho\right)$$

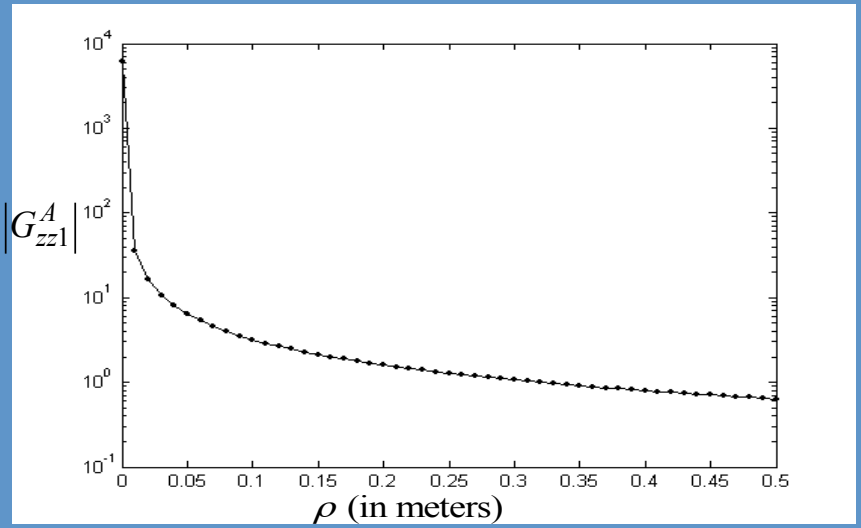
Quasi-static part is calculated analytically

- Through the analytic extraction of “true” quasi-static images that capture the correct singular behavior close to the source
- An arbitrary number of quasi-static images can be extracted analytically
  - The number of the quasi-static images extracted dictates the decay of the dynamic part
- The extraction of the quasi-static part does not introduce any error in the solution since everything is done analytically and in closed-form

Prototype Code: Evergreen



Example of a 4-Layer Structure



Solid Line: Numerical integration
Dotted Line: RFFM

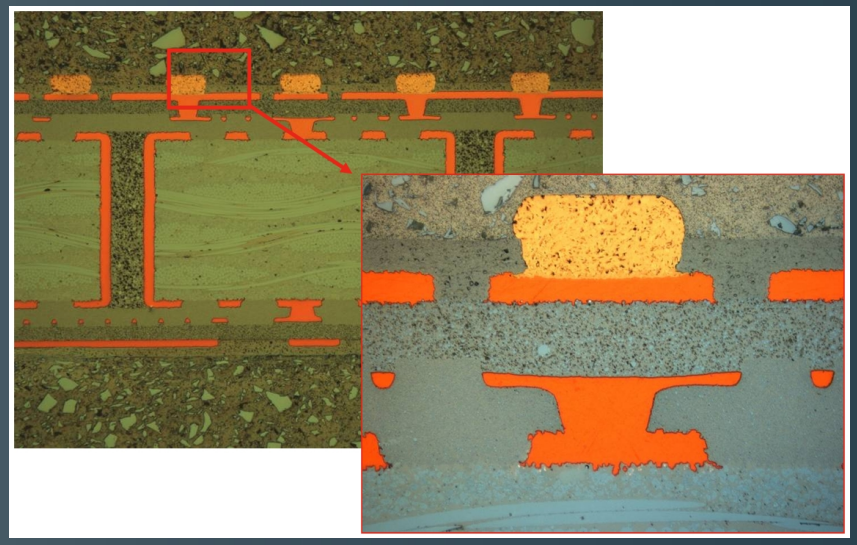
- User-provided input
  - Layered medium geometric/material properties
  - Frequency
  - VECTFIT parameters: number of poles and number of iterations

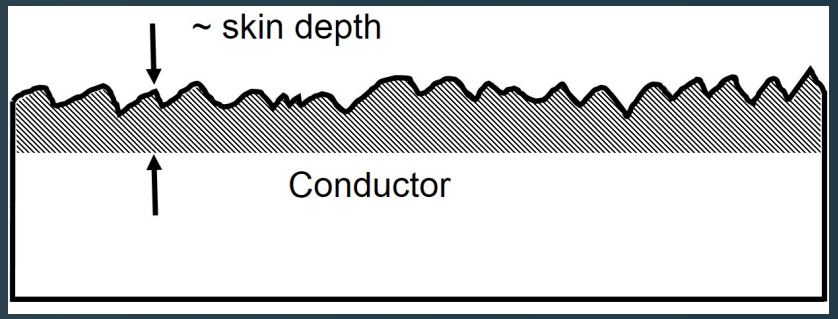
Key attribute of the method: Simplicity

- **At low frequencies, quasi-static behavior dominates**
  - Captured by the quasi-static images
- **At high frequencies, cylindrical wave behavior dominates**
  - Captured by the poles in the fitting of the dynamic part of the spectrum
- **Close to the source the fields exhibit singularities**
  - Captured by the quasi-static images
- **In the far-field region propagating modes are the only contribution**
  - The "true" poles of the spectrum are included in the solution during the fitting of the dynamic part
- **Only one expression is necessary for the accurate representation of the fields anywhere and at any frequency**

Modeling conductor surface roughness(*)

- At multi-GHz frequencies, skin depth is comparable to the root-mean-square (rms) height of the rough surface
  - Conductor surface roughness impacts the electromagnetic behavior of interconnects and high-frequency electronic devices is not negligible





(*) X. Ma, J. Ochoa, and A.C. Cangellaris, in *Proc*. EPEPS 2013.

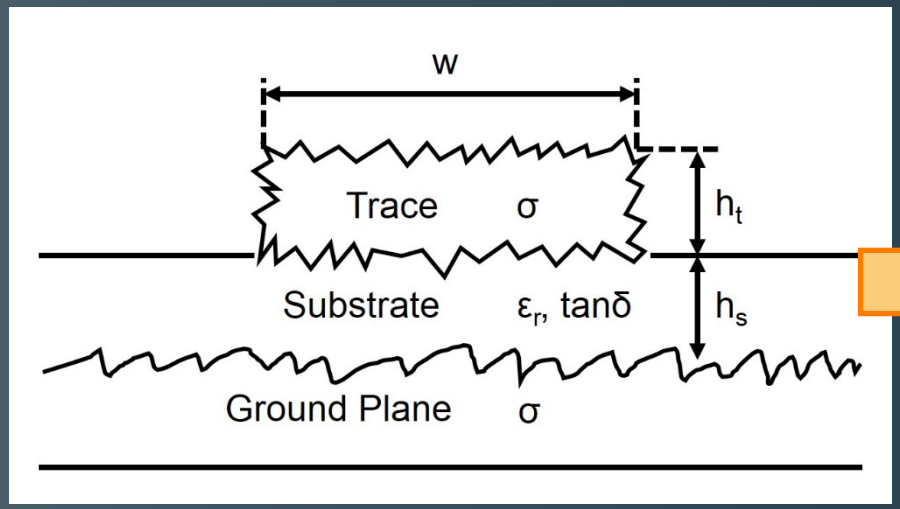
Power absorption enhancement factor

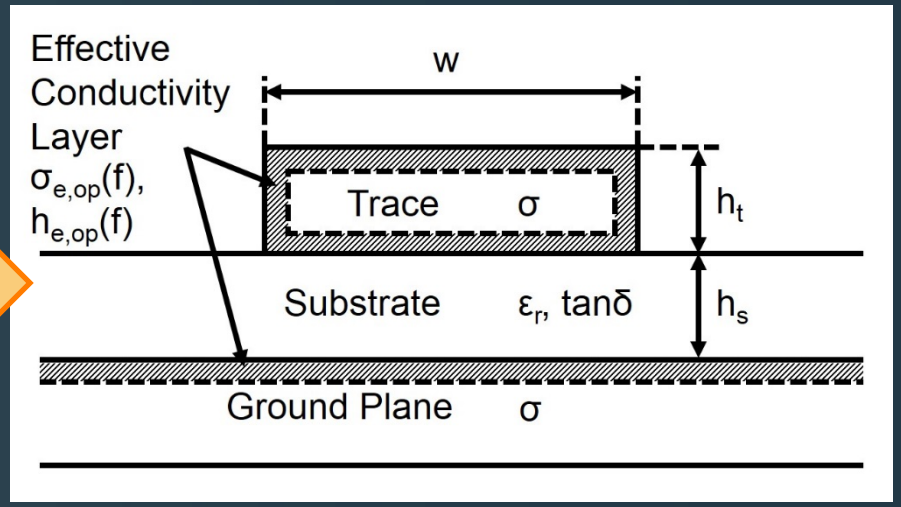
$$K_{SR} = \frac{P_{rough}}{P_{smooth}}$$

- Ratio of power dissipated per unit length and width for rough and smooth surfaces
  - Quantifies how roughness increases power absorption
- Stochastic model (*)
  - Random rough surface with roughness profile described by spatial power spectral density (PSD) function
  - Small perturbation method (SPM)

(*) L. Tsang, X. Gu, and H. Braunisch, *Microwave and Wireless Components Letters, IEEE*, vol. 16, no. 4, pp. 221–223, 2006.

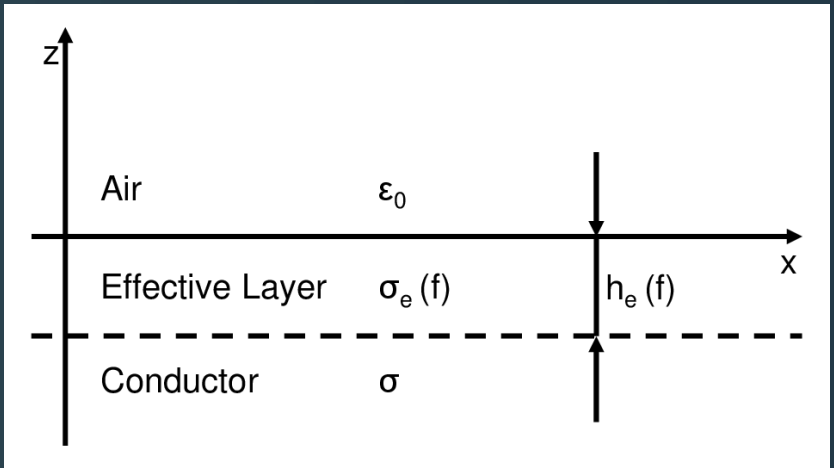
Modeling smooth surfaces is simpler





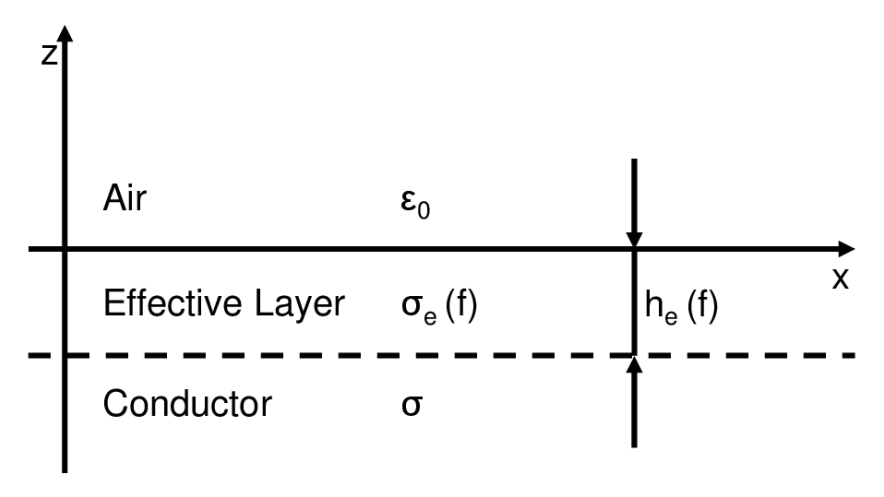
Frequency-dependent compound conductor model

- Starting point:
  - K_{SR} for rough conductor
- Deriving model parameters:
  - Express K_{SR} for the compound conductor model in terms of the thickness and conductivity of the effective conductivity layer
  - Obtain thickness and conductivity of the effective conductivity layer through interpolation
- Goal:
  - Same K_{SR}

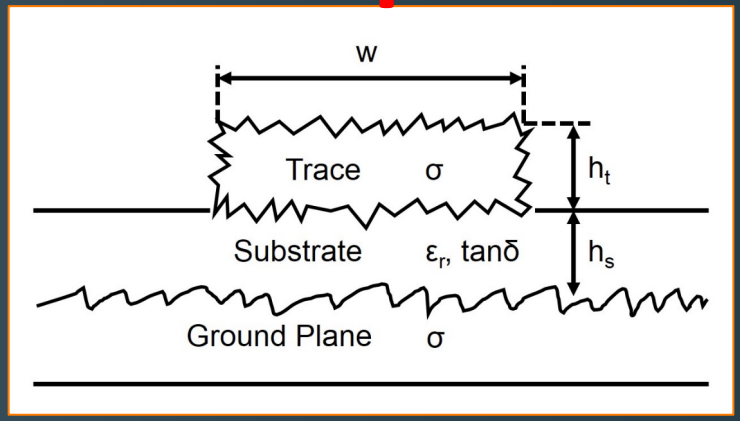


Frequency-dependent compound conductor model

- Effective conductivity layer conformal to conductor surface with frequency dependent thickness and conductivity
  - Conductivity of the bulk conductor remains unchanged
  - Outer dimensions of conductor remain unchanged

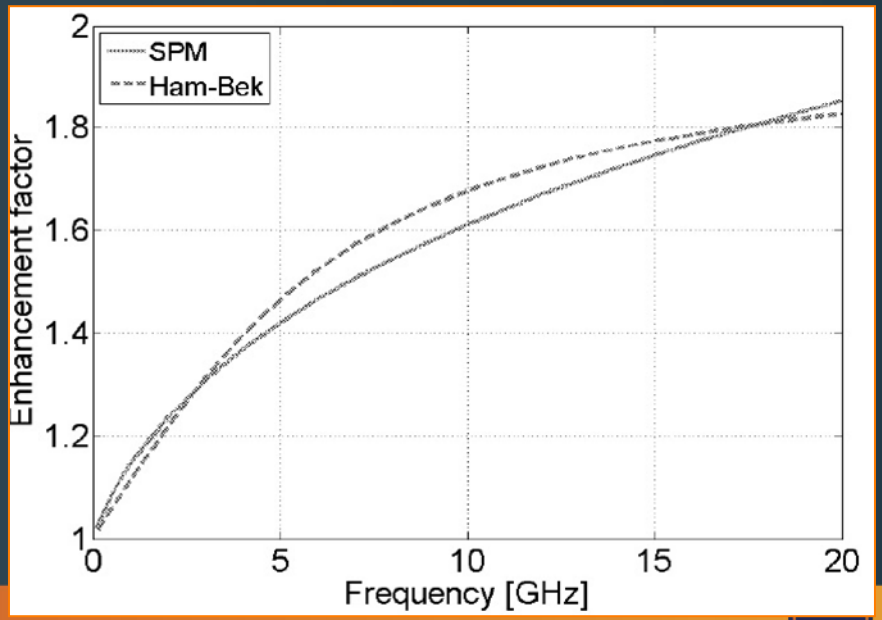


Impact of surface roughness on microstrip attenuation



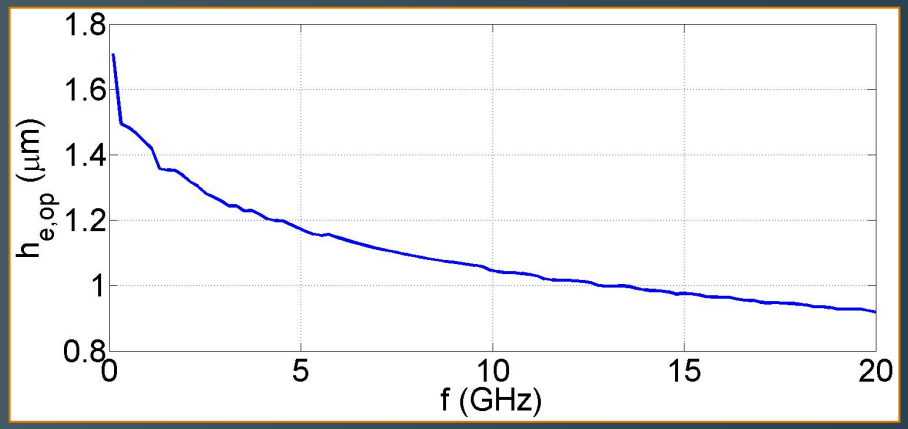
Test structure(*)

- $h_s = 30.6\mu m$
- $h_t = 15.3\mu m$
- $w = 65.5\mu m$
- $\varepsilon_r = 3.4$
- $\tan\delta = 0.017$
- $\sigma = 4.5 \times 10^7 S/m$

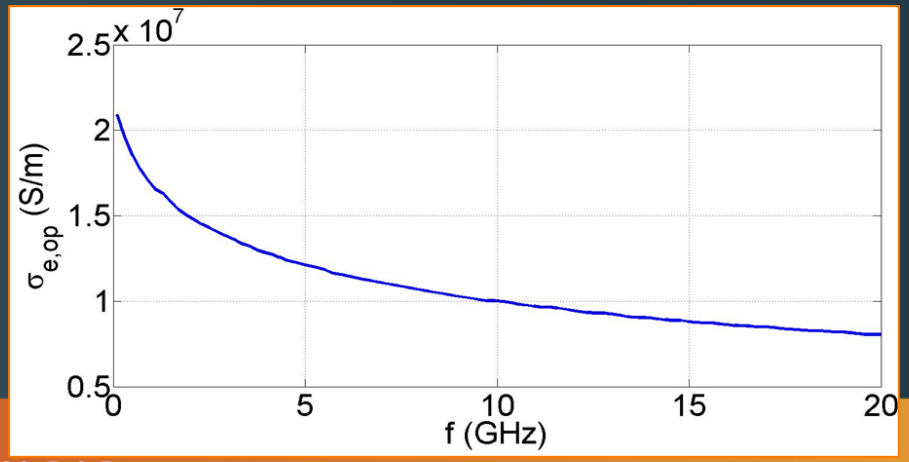


(*) H. Braunisch, X. Gu, A. Camacho-Bragado, and L. Tsang, *in Electronic Components and Technology Conference, 2007. ECTC '07. Proceedings*. 57th, 2007, pp. 785–791.

Frequency-dependent thickness

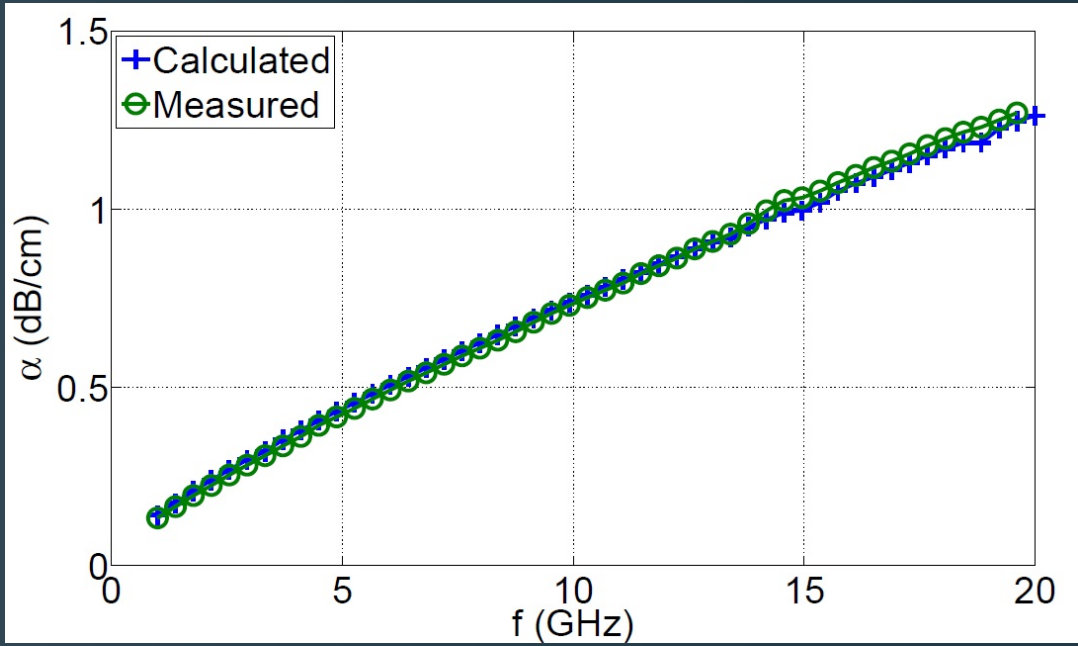


and conductivity



Model facilitates use of commercial solvers

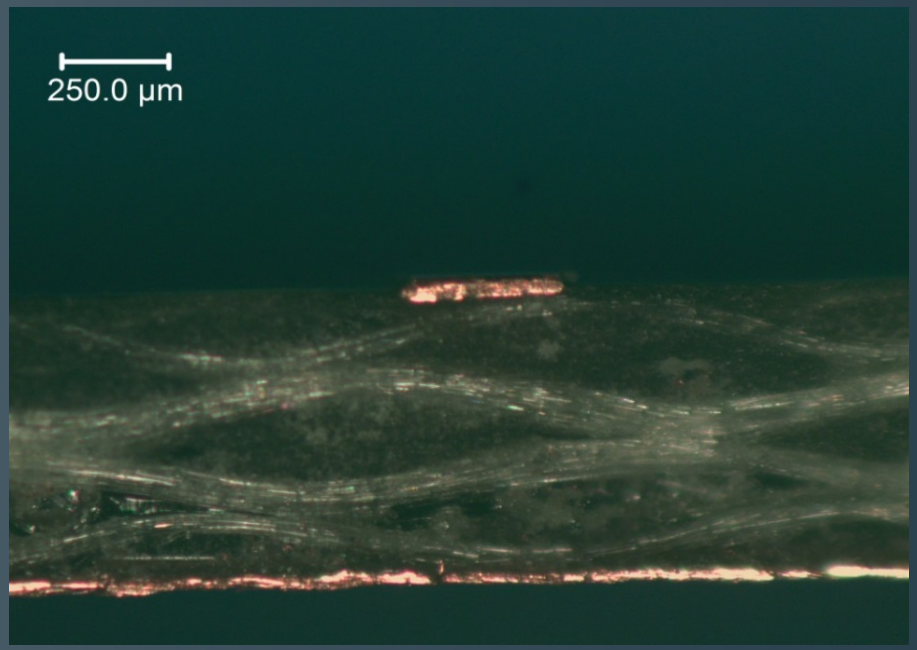
- Attenuation constant calculated using Ansoft Q3D extractor with proposed compound conductor model
- Measured data from (*)



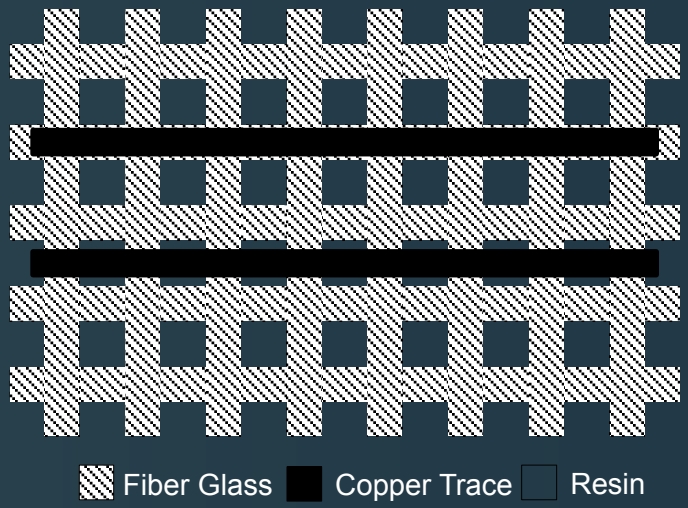
(*) H. Braunisch, X. Gu, A. Camacho-Bragado, and L. Tsang *in Electronic Components and Technology Conference, 2007. ECTC '07. Proceedings*. 57th, 2007, pp. 785–791.

Impact of PCB fiber weave on differential signaling(*)

Cross sectional view of PCB made of woven fiberglass and epoxy resin.



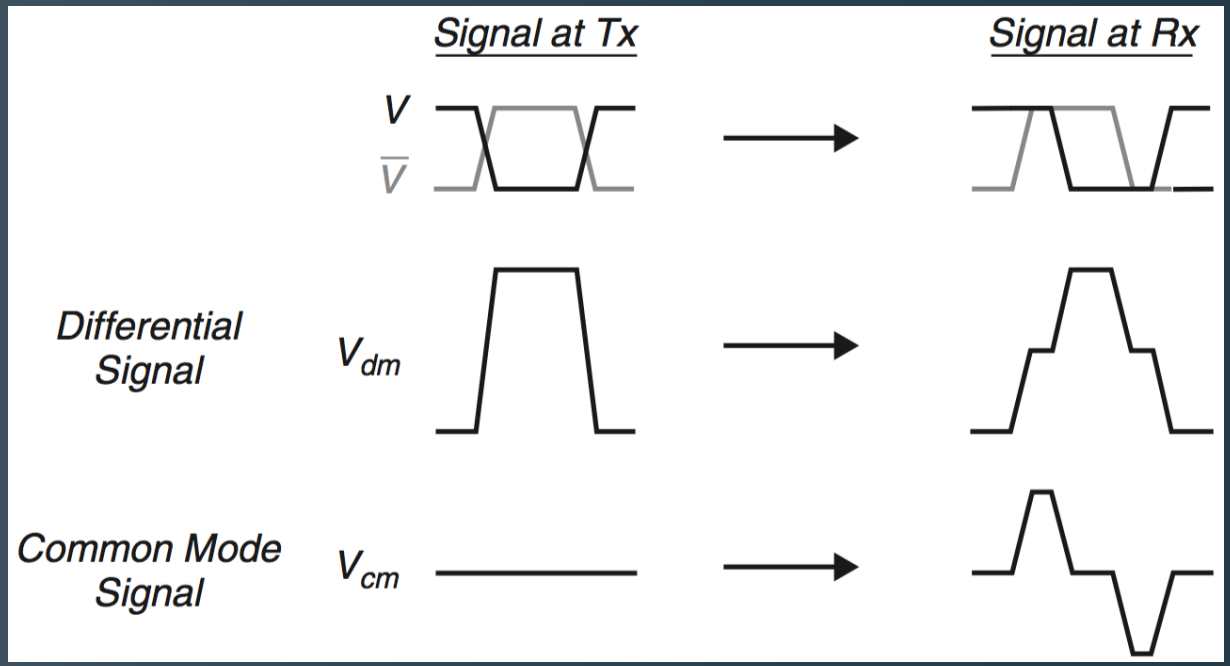
Top-view sketch of PCB



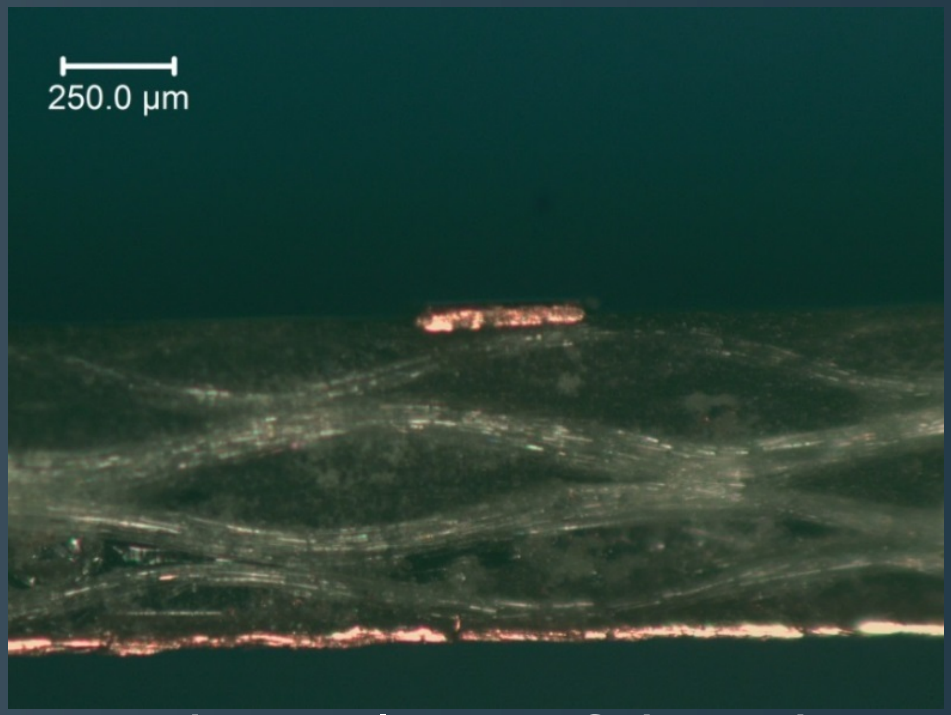
(*) T. Zhang, X. Chen, J. Schutt-Aine, and A. Cangellaris, *in Proc. 18th IEEE Workshop on Signal and Power Integrity (SPI)*, Ghent, Belgium, May 2014.

Fiber weave induced intra-pair skew

is a significant signal integrity concern in high-speed/high data rate channels.



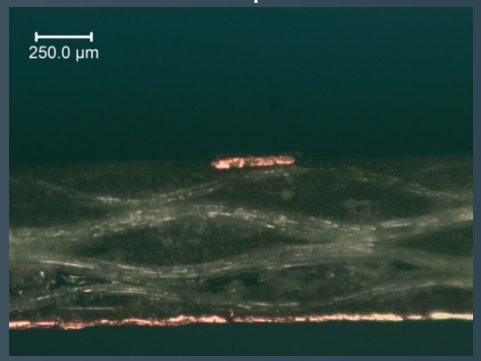
EM modeling challenges due to substrate complexity



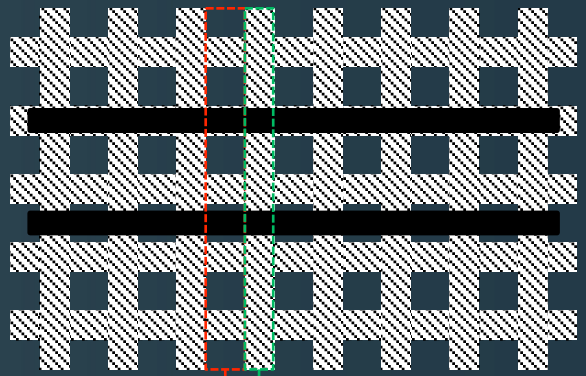
The randomness and complexity of the substrate topography hinders the use of 3D field solvers for predicting signal degradation due to fiber weave.

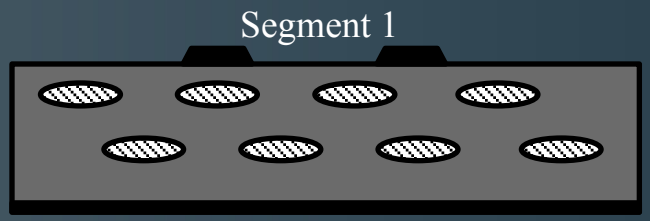
Divide and Simplify

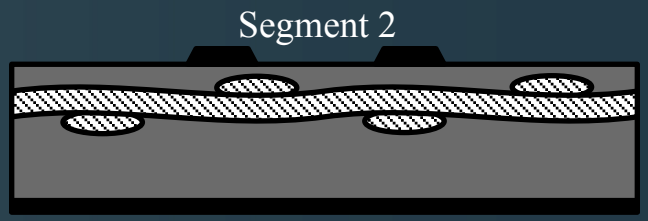
Cross-sectional photo of PCB



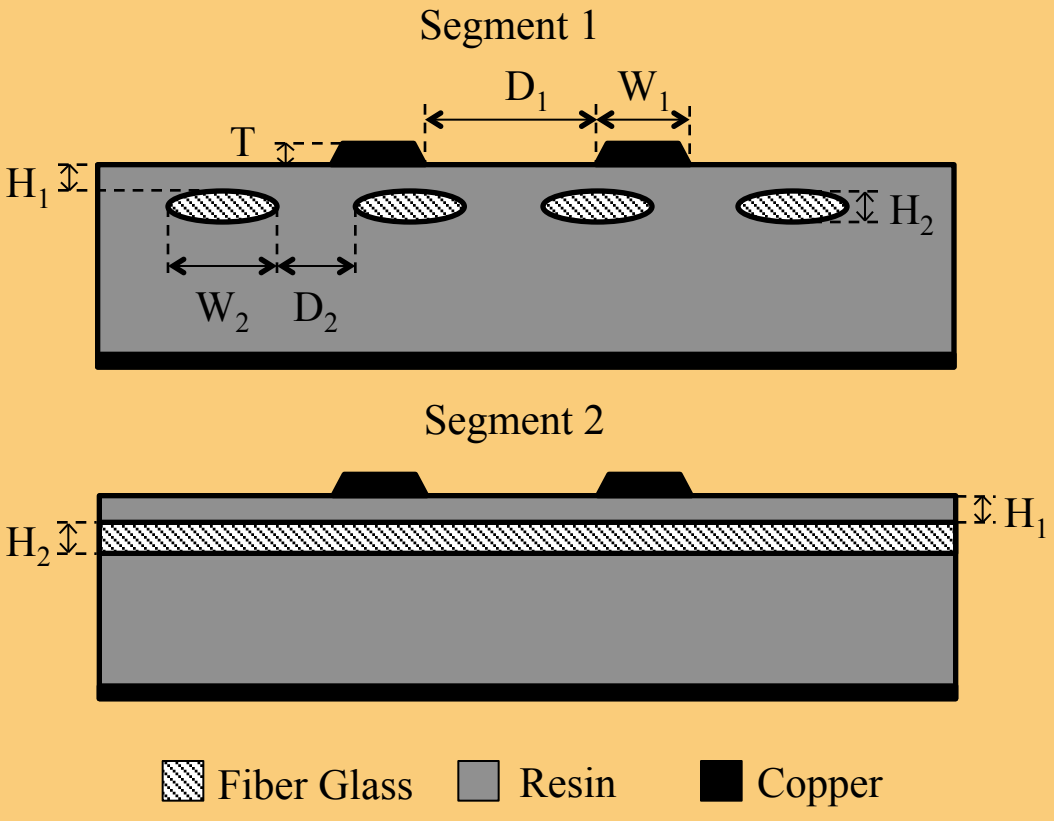
Top-view sketch of PCB







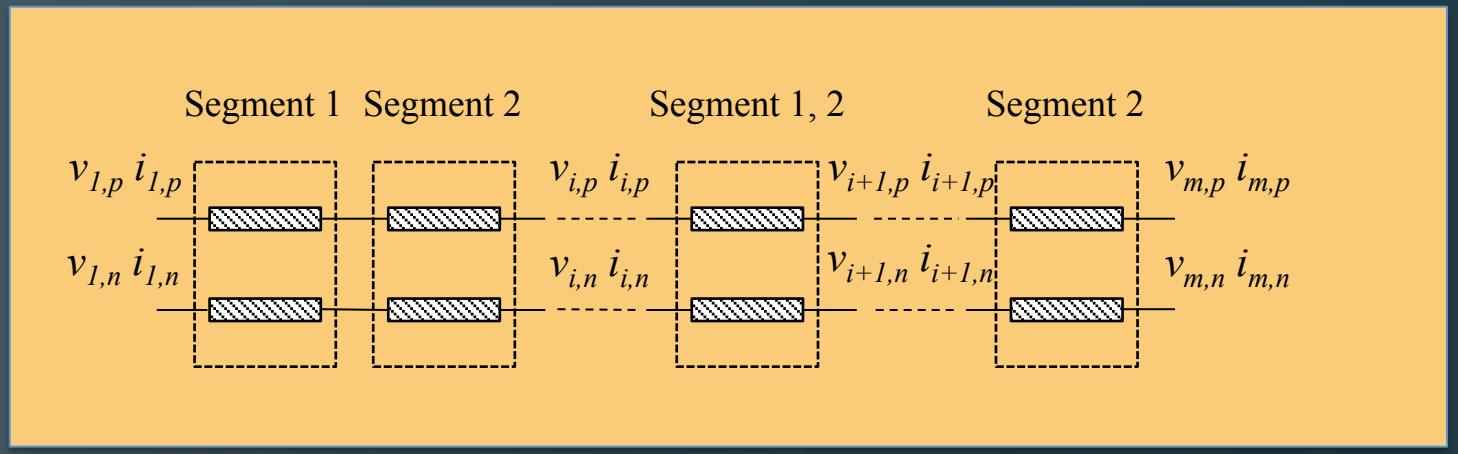
Model Parameters



W_1	W_2	D_1	D_2	H_1	H_2	T
0.1mm	0.2mm	0.1mm	0.2mm	0.01mm	0.06mm	0.015mm

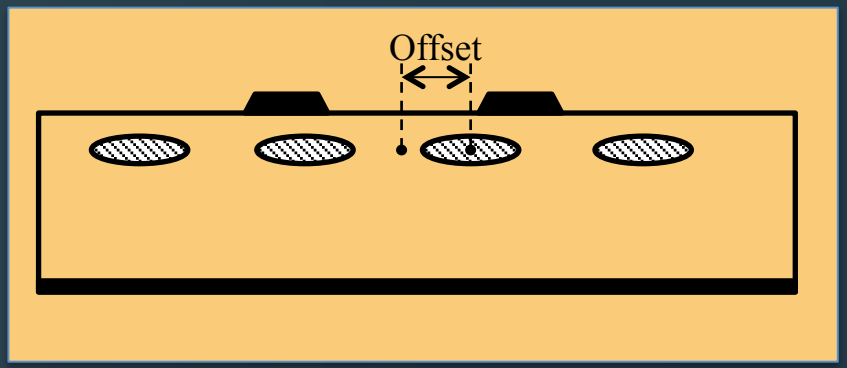
ABCD matrix modeling of the interconnect

ABCD matrices of alternating Segment 1 and Segment 2 are cascaded to obtain the overall ABCD matrix of a differential transmission line



Introducing randomness in the model

- Randomness of trace location on PCB captured through the "offset" distance between the center of fiber bundle and the midpoint of two traces
- The random variable "offset" has a uniform distribution

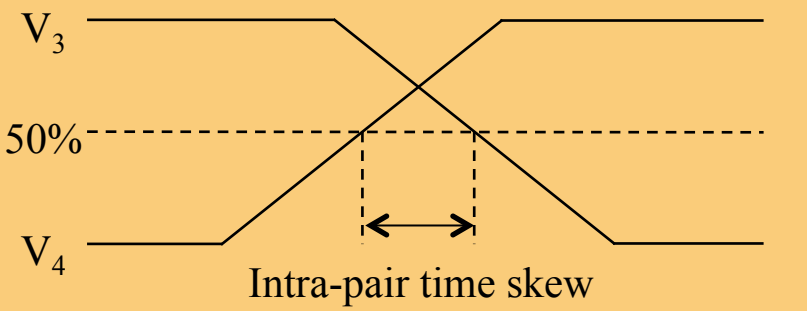


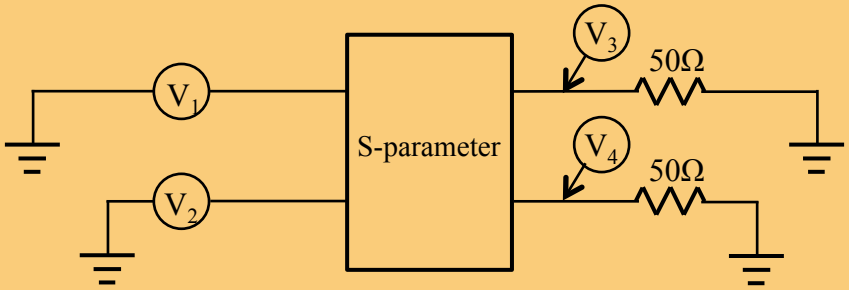
A specific example

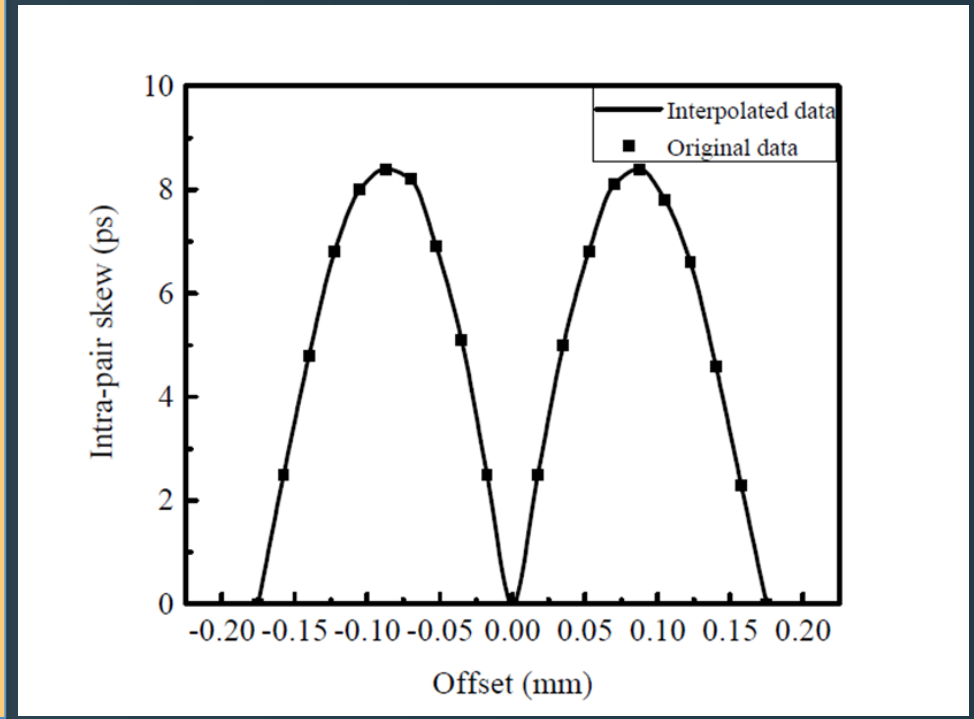
- A differential pair of length **L = 10cm** on a typical PCB with **106 weave pattern**
  - **106 pattern**: 56x56 threads/inch yarn count and 17.9x17.9 mils yarn pitch (*)
  - Segment is calculated as **l = 0.2mm**
  - Dielectric constant of fiberglass is **$6.6\epsilon_0$**; dielectric constant of resin is **$3.2\epsilon_0$**
- Random variable "offset" has uniform distribution within range [-0.175mm, 0.175mm]

(*) L. Simonovich, "PCB Laminate Construction," Dec 2010. [Online]. Available: http://blog.lamsimenterprises.com/2010/12/14/

Using intra-pair skew
to quantify the impact of fiber weave

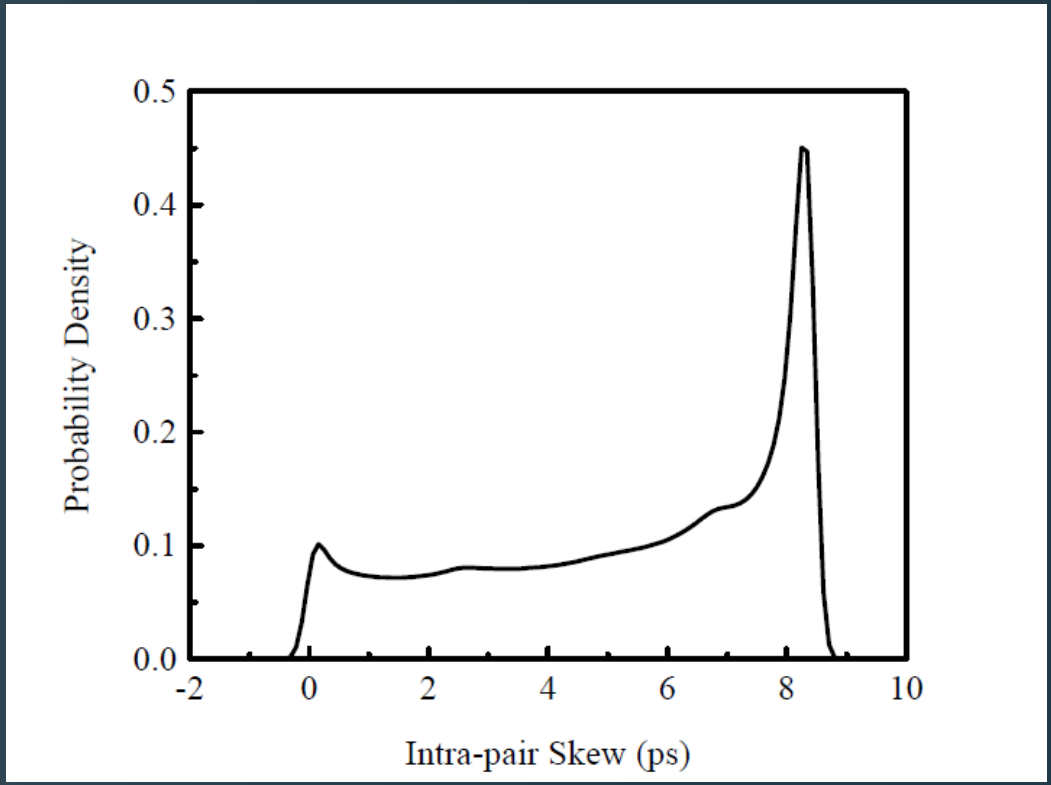






PDF of Intra-Pair Skew is not uniform

- PDF of intra-pair skew for a 10cm-long differential pair.
- Peak of PDF occurs at 8ps, which is very close to the maximum intra-pair skew.



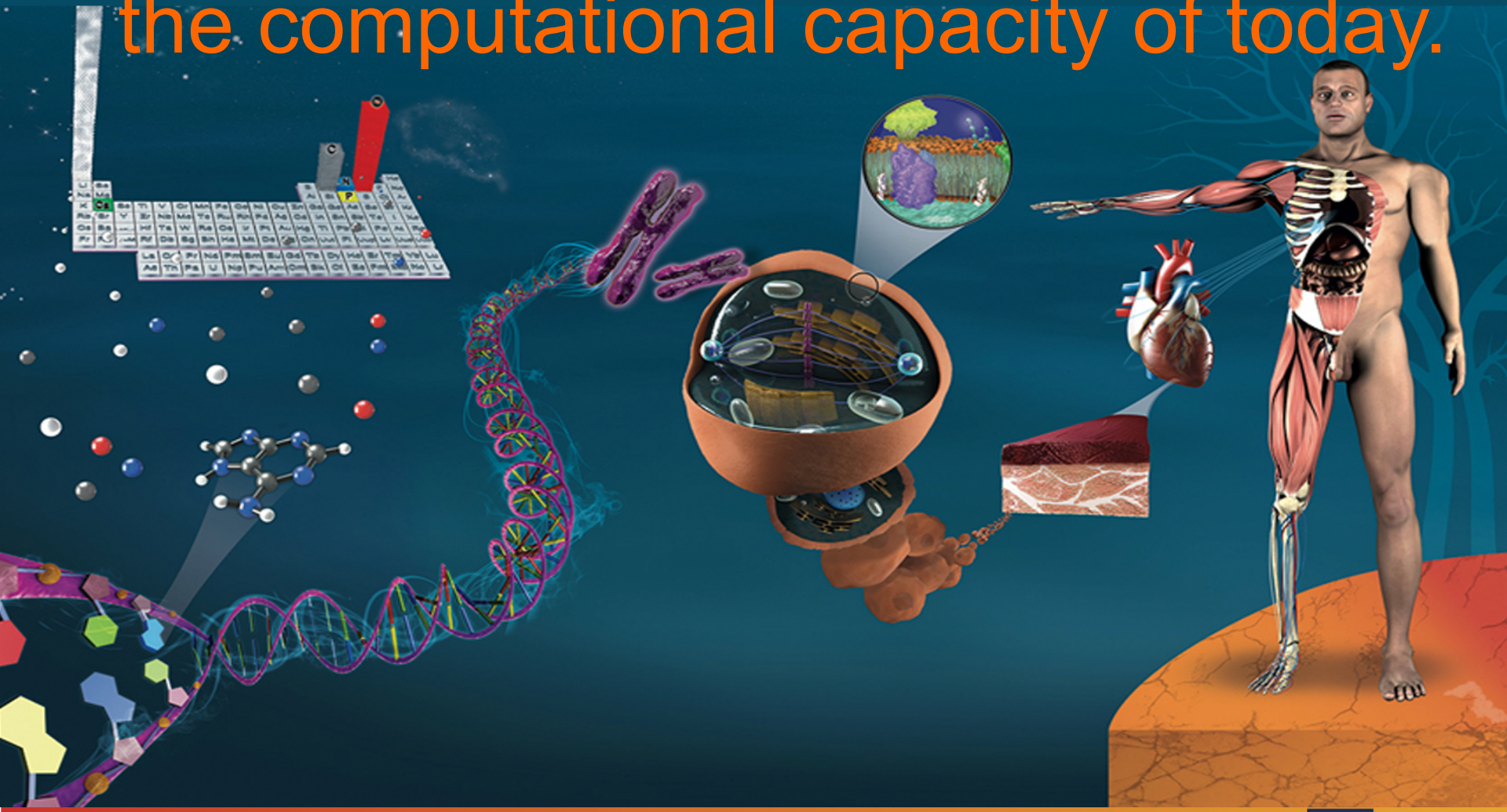
Recommendation:
Design for worst case scenario

Percentage	Intra-pair skew
10%	>8.30ps
20%	>8.03ps
30%	>7.50ps
40%	>6.78ps
50%	>5.91ps

The computational needs of tomorrow

overwhelm

the computational capacity of today.



Making things
as simple as possible
is not easy.

Yet, it is essential for us
to anticipate and influence
the future.